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HOOK ECHOES ON RADAR

BY
Lt John W. Stryker
Detachment 23, 6th Weather Wing

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EDITOR'S PREFACE

The investigations and theoretical conceptions of the late Prof. Ferdinand C. Bates concerning severe storms are well-known and were recently presented in the AMS Bulletin (Vol. 51, No. 6, June 1970). This study attempts to correlate the thoughts of Prof. Bates with the formation of the hook-type echo seen on the weather radar scopes, frequently in close proximity to observed and reported severe weather conditions. This report is published by USAF ETAC as a plausible explanation of the hook-echo phenomenon and, as such, is believed to warrant the consideration of forecasting and observing personnel within the Air Weather Service.

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HOOK ECHOES ON RADAR

Introduction

Since the original use of radar as a detection device for precipitation patterns, various echo patterns have been diagnosed as belonging to specific weather phenomena. Of these patterns, the hook echo has been widely discussed in association with tornadic activity. While most echo patterns are reasonably explained by the associated weather, there seems to be a lack of connection between the hook echo and the tornadic activity. Yet a very high correlation between the occurrence of tornadoes and the appearance of hook echoes on weather radar scopes does exist.

The relationship between the hook echo and the tornado can be described by use of a thunderstorm and tornado model developed by the late Dr. F. C. Bates [1]. According to this theory, a structure is developed which will account for the hook echo.

Theory of Tornado Formation

A steady-state storm development is the basis for the theory. A sufficient number of severe storm parameters [8] to produce the conditions necessary for severe weather activity are originally assumed. As the thunderstorm activity develops, there is the possibility that one or more thunderstorm cells will develop a rotation within the structure of the cell (see Figure 1). This rotation will intensify as the cell matures, unless it is interrupted by movement outside of the parameter source, terrain effect, or unfavorable effects, such as strong shear aloft.

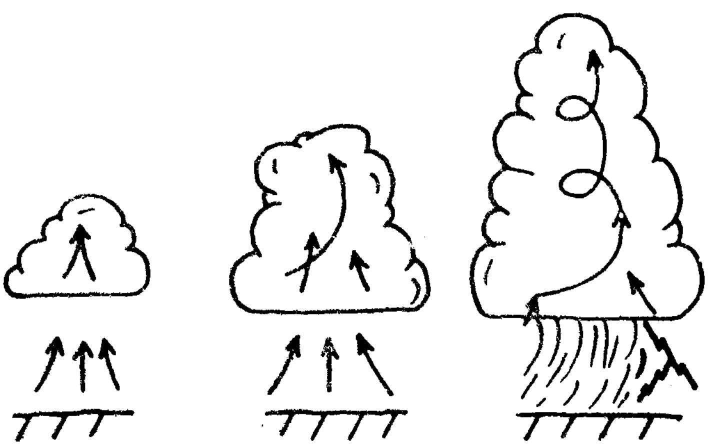

Figure 1. Storm Development. Original development begins with the same characteristics of the air-mass thunderstorm. The strength of the vertical velocity causes the rotation to start within the cell.

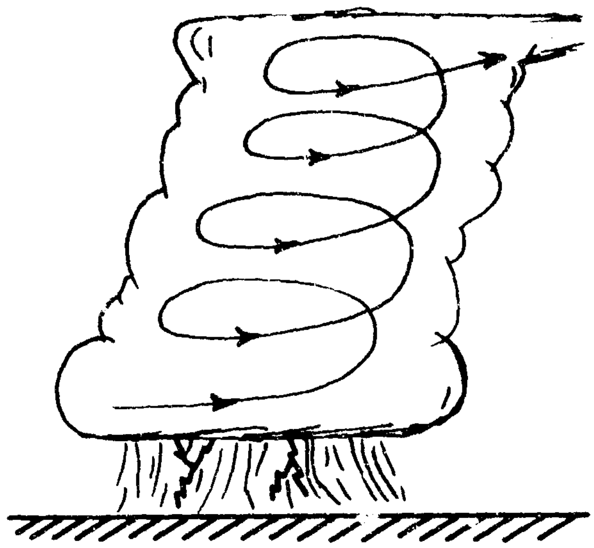

Figure 2. Leaning Stage Storm. The leaning stage of the steady-state storm usually exists from near the onset of showers through the hailstorm stages. The leaning structure is due to the increase of wind velocity in the vertical.

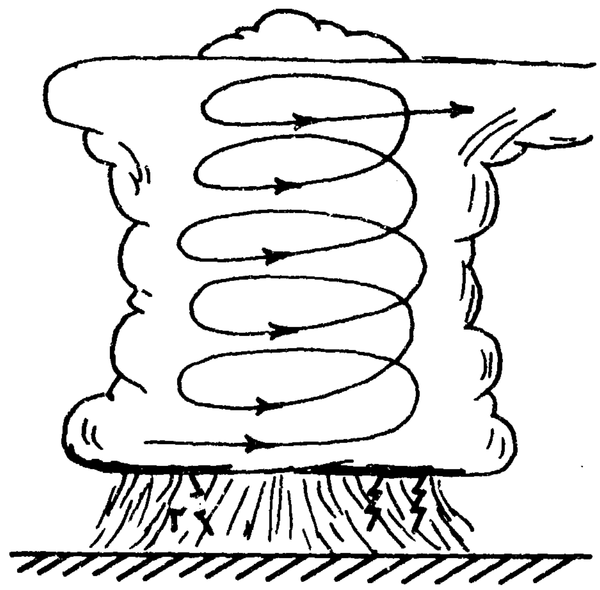

Figure 3. Erect Stage Storm. The erect stage of the steady-state storm will extend above the tropopause and will have a movement that is similar to a vortex in a flow system of hydrodynamics.

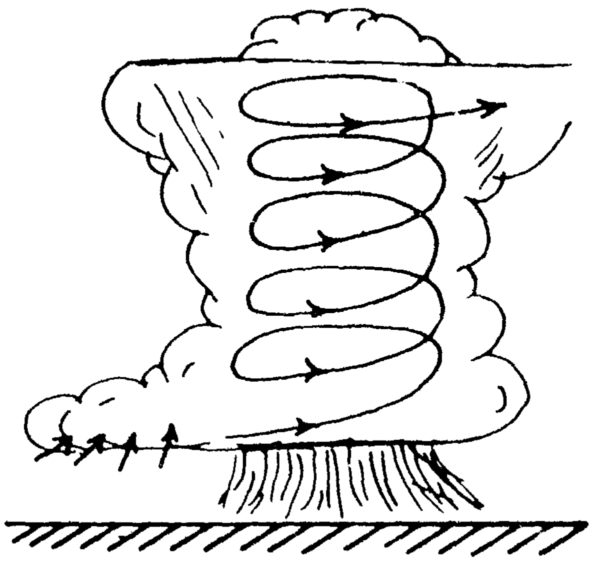

Figure 4. Windward Side Convergence. Low-level convergence is induced in the windward area of the cell causing further development. This flanking side development can be quite rapid.

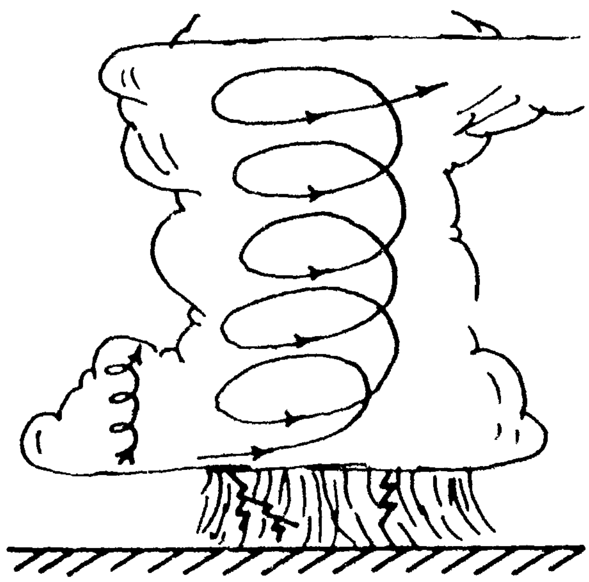

Figure 5. Flanking Side Cell Development. New cell development on the flanking side of the steady-state storm can have rotation in early stages.

Due to the normal wind shear aloft favorable for severe storm development, the cell in the early stages will lean toward the lee side (see Figure 2). As the rotation intensifies, the cell will tend to become erect in the flow aloft (see Figure 3).

This erect steady-state storm can exist and continue on for a period of time which stretches into hours. It will continue as long as it remains in the source area where the required parameters exist. It can be disrupted by terrain effect, such as a mountain range or another large dynamic force which would disturb the circulation within the cell. Once the erect steady-state storm has formed, a col area will tend to develop near the windward side of the storm. This enhances convergence in the flow upstream from the cell. As long as the conditions that caused the original development exist, this added convergence increases the potential for the spawning of a new cell in the windward flow (see Figure 4) [9]. Similar rotation is possible in the convergence zone cell (see Figure 5). As this new cell grows, the wind shear tends to cause this new cell to lean towards the mature erect cell (see Figure 6).

There is a tendency for a connection between cells due to the flow. The new cell normally develops tops near 20,000 feet before the circulation of the cell intrudes into the steady-state storm (see Figure 7). If the rotation has matured sufficiently to withstand the disturbances in the outer portions of the erect storm, it will connect into the larger rotation.

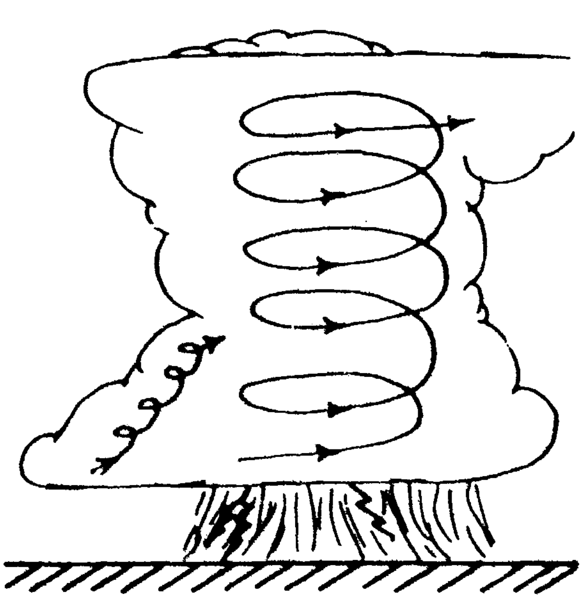

Figure 6. Development of the Flanking Storm. Under ideal conditions the flanking storm will lean towards the erect storm.

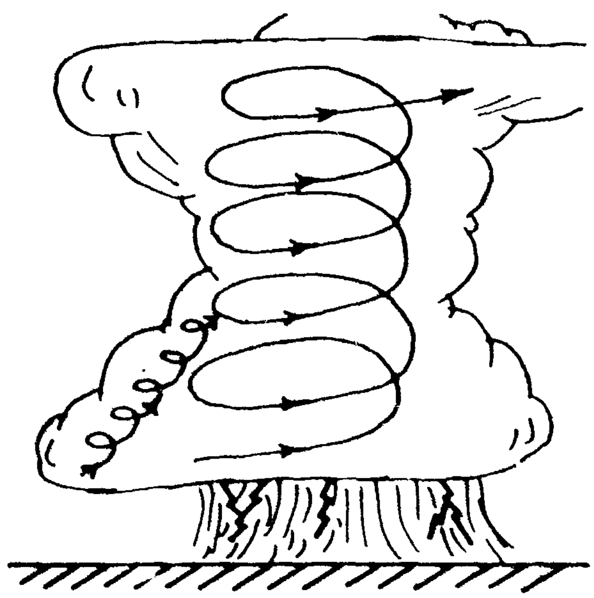

Figure 7. Junction of the Two Storms. The flanking-storm circulation can intrude into the steady-state storm between 20,000 and 40,000 feet.

"When the shear is sufficient to cause a cumulus in the flanking line to lean over and connect with the blocking thunderstorm aloft, the evolution of the tornado and one of the most hazardous structures for aeronautical operations is begun. The thunderstorm itself sees the connected updraft as an alternative duct for its own updraft and demands a commensurate mass-rate of flow. The weaker updraft of the connected cumulus cannot supply this, so its central pressure aloft is sharply reduced. This calls into being a radial inflow which, with the slight rotation of the cumulus updraft that must always exist, leads to the formation of a violently-rotating tube in the heart of that updraft by the process of conservation of moment of momentum in a central pressure-gradient force field. As the tube forms and blocks further inflow from the side it evolves downward through the updraft. Similar connections and tube evolutions may take place in cumuli further outward in the line as the initial tube evolves downward. Below some of the cumuli the tubes may develop no more than invisible vortices, revealing themselves only as dust-whirls at the surface (or water-sworls over a marine surface). Indeed, these may be all that form in many such lines. Occasionally, however, an optimum termination of one or these tubes may continue to intensify with decreasing central pressure until the condensation pressure of the air involved is reached and the tornado funnel appears. Note, however, that these tubes may in any case have tornadic or near-tornadic intensity in and below the flanking line." [7] (See Figure 8.)

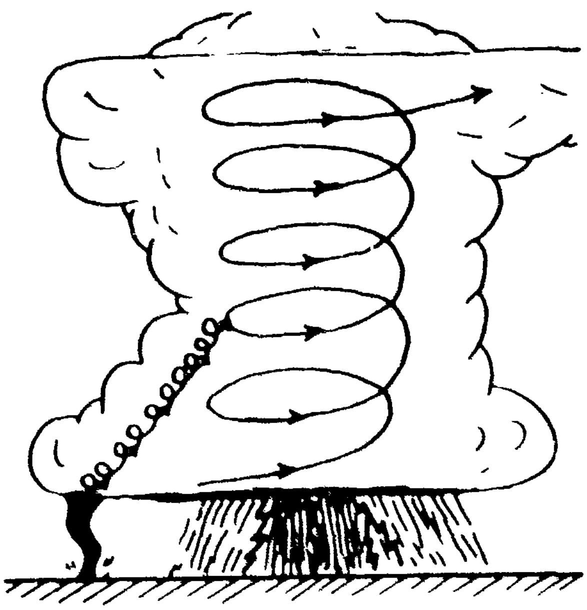

Figure 8. Tornado Initiation. The development of the tornadic vortex after connection of the flanking cloud to the base and sometimes to the surface (after Bates [7]).

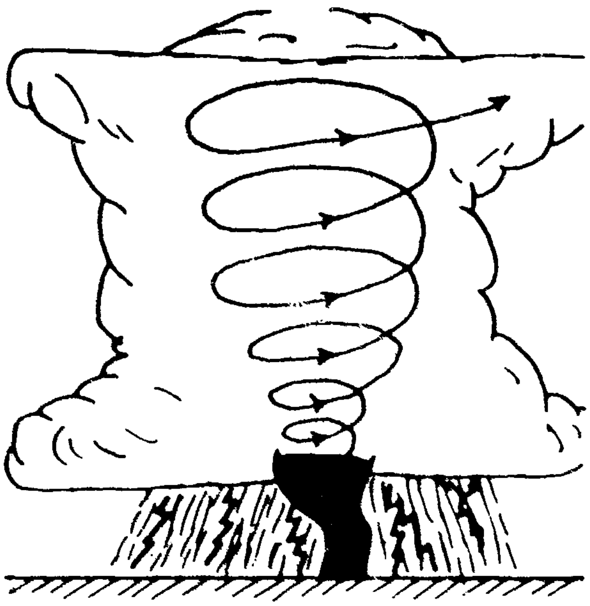

Figure 9. Steady-State Tornado. This type of tornado has the circulation of the main storm as its vortex (after Bates [7]).

The tornadic vortex can continue until it is drawn so close to the erect storm that its circulation is destroyed, or it may form and dissipate rapidly due to the unstable nature of weaker vortices. Minor changes in terrain, or rough terrain, can cause lifting of the stronger tornadoes and dissipation of weaker ones. Favorable terrain for convergence can cause intensification of the vortex.

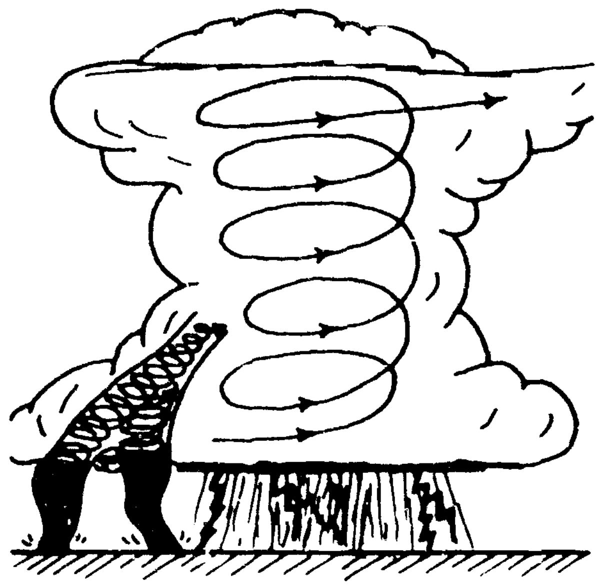

Figure 10. Multiple Vortex Formation. The development of cumulus will continue in the flanking line and more than one vortex is possible. Paths of destruction have suggested this.

If the rotation within the smaller cell had developed to a point where it was nearing steady-state conditions prior to intrusion into the larger cell, it is possible that it could take over the circulation of the larger cell and develop into the steady-state tornado with massive destruction in a long path, with little or no breaks in the path (see Figure 9).

Redevelopment can occur in the favored convergence area with new tornadoes developing upstream from the dissipated or presently-active tornadoes. It is not unusual to see individual paths along a line with short periods of life and a curvature toward the larger cell at dissipation (see Figure 10).

Hook Echo Relationship

The relation of this tornado model to the hook echo can now be shown. The strongest portion of the main echo is considered the erect steady-state cell. The main echo will have a high intensity of strong to very strong and tops will normally exceed the height of the tropopause. Movement may be erratic and not paralleled with the low- or mid-level wind flow or associated squall lines. This is due to its nature as a vortex (see Figure 11).

The hook is a small-scale feature compared to the main cell. It extends into the low-level windward flow relative to the main storm and is normally ten miles or less in length (see Figure 12). The initial appearance of the hook is rather rapid when compared to normal echo development. The duration of this hook echo varies from a few minutes to an hour or more. The hook usually will appear prior to the development of a vortex.

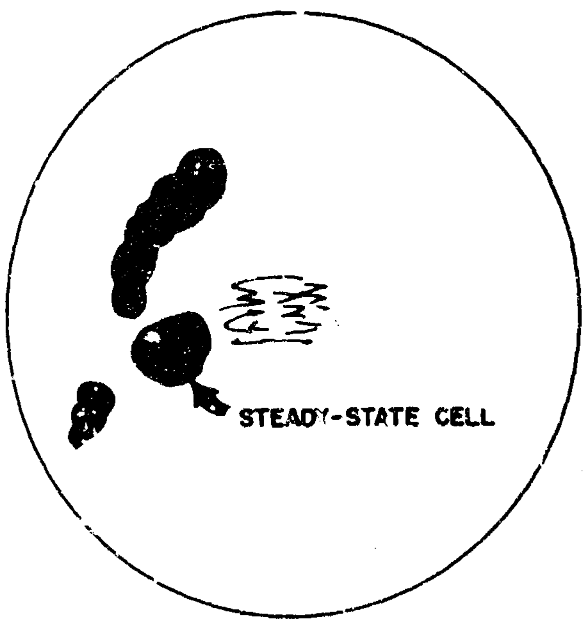

Figure 11. Sample PPI Scope. Return shows a steady-state cell that has developed in a line of thundershowers and suddenly moves ahead of the line of echoes.

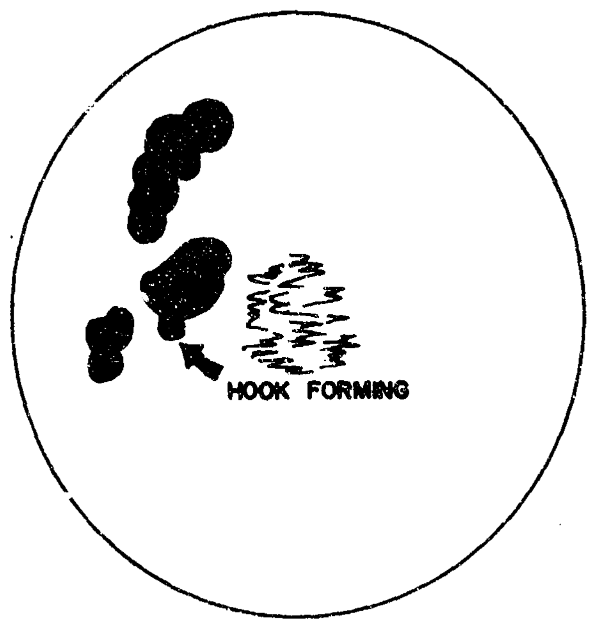

Figure 12. Hook Echo Formation. The hook echo forms in the convergence area of the main echo, as indicated.

The hook portion of the echo corresponds to the development of the newer storm in the convergence zone of the steady-state storm. Also, it is sometimes formed by a smaller and weaker cell moving into the zone which is favorable for the connection of the rotating updrafts (see Figure 13). The intensity of the echo can vary greatly during this period and is very dependent upon the extent of development that has occurred in the less mature cell prior to the connection of the two cells. The intensity normally will increase rapidly as the vortex develops. Because of the frequent short-life periods of many vortices, this increase in intensity may easily go unobserved before dissipation.

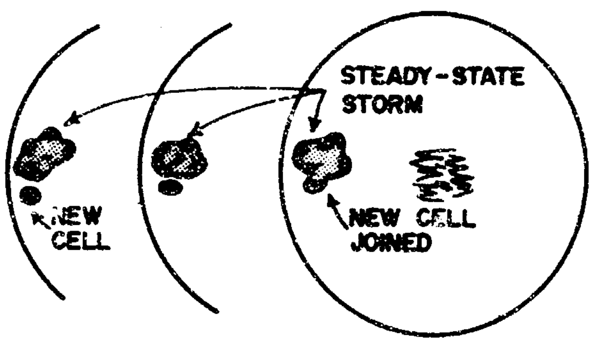

Figure 13. Union of Two Cells. A steady-state storm echo is presented with a newly-developed cell moving toward it and connecting.

The tops of the hook portion might not exceed 20,000 feet in height or might, in many cases, extend above 40,000 feet. This again is dependent upon the nature of the storm prior to connection of the two vortices. Most of the hooks observed by this author have been near 20,000 feet with tops of the main cell exceeding the tropopause. The very difficult task of being able to observe both cells on the RHI scope simultaneously requires an ideal location of the radar and storm (see Figure 14).

Figure 14. Idealized RHI Scope Patterns. Various patterns show the main echo and hook in line. This is an ideal situation which is difficult to achieve.

The shape of observed hook echoes on the PPI scope varies considerably, depending on the direction of the various wind shears affecting development.

The definite hook shape is due to the change of direction of the wind in the vertical. On certain radars with relatively high attenuation, such as CPS-9, a high intensity vortex may be attenuated by itself or by the main storm, resulting in the hook echo being hidden (see Figure 15).

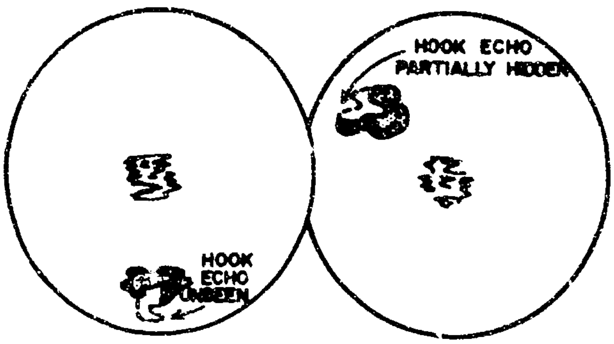

Figure 15. Attenuation of Hook Echo on PPI Scope. The hook echo is attenuated or partially attenuated on the PPI scope.

There is a great amount of fluctuation associated with most of the observed hook echoes, varying from clear-cut and intense displays to indistinct and weak echoes (see Figure 16). This is related to the intensity of the vortex that exists within the hook echo. The weaker echoes are usually either the early stages of vortex development or funnel clouds only. The clear-cut intense hook echoes are closely related to the track of destruction on the surface. The initial weaker portion of the hook can be indicated on radar long before the occurrence of the actual tornado.

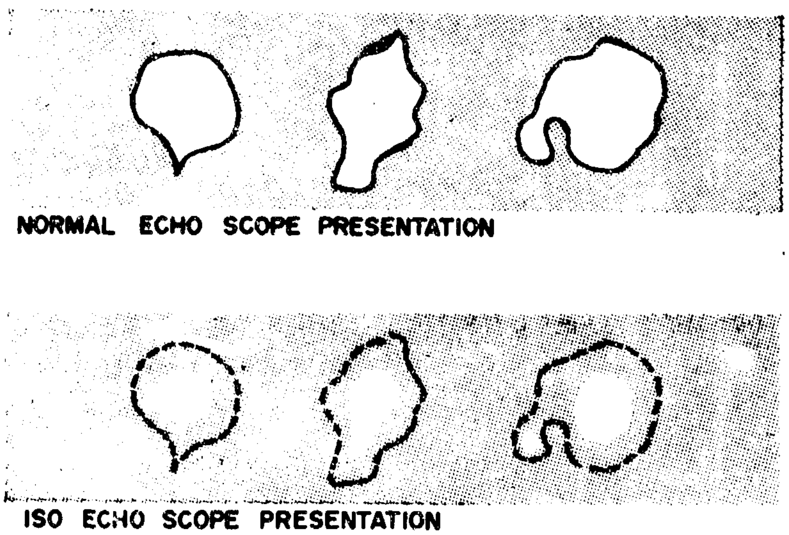

Figure 16. Simulated Radar Returns. These echoes represent various intensities of hook echoes under normal scanning and also gives ISO echo presentations of the same returns.

Exceptions

It must be stated that not all hook-shaped echoes that appear on radar should be considered as possible tornado-producing clouds. Based on the "Bates Model," the best means to determine a "suspect hook" would be the intensity of the main echo. At the present time, there is no fixed criteria for the intensity setting of a tornado-producing storm. Funnel clouds have been sighted from echoes which had only moderate or weak intensities. Also, there have been tornadoes without the appearance of a hook-shaped echo on radar.

This situation may be partially explained by the collision of two fairly mature, steady-state storms. One of two things must happen in this case: 1) either the circulation of the two storms will destroy each other and the storms will dissipate, or 2) one of the two storms will have a sufficiently strong circulation to dominate the other. When this happens, the weaker circulation can become the vortex, resulting in a very violent tornado due to the original intensity of the circulation in the weaker mature cell.

Another exception to observing a hook echo is the possibility of the vortex of the steady-state storm becoming the tornadic vortex. This development could start with a hook echo; however, as the tornadic vortex intensifies and is drawn nearer the circulation of the main storm, it withstands the outer disturbances and replaces the circulation of the main storm. While the probability of this type storm is very small (estimated to be 1-5% of all tornadoes), it can explain the long-duration tornado which sweeps a continuous path of destruction through the Great Plains and Midwest.

Hooks that have no visible tornado or funnel clouds sometimes are due to a flanking cloud that forms without sufficient wind shear to connect the systems. There have been instances, however, of clear vortices existing with the hook echoes. These clear vortices may be indicated by dust swirls at the surface or the sounds normally associated with tornadoes. They usually result from the lack of moisture at the point of occurrence or the lack of condensation nuclei to form the visible vortex. This situation may also exist when the intensity of the vortex is too weak to produce condensation.

Conclusions

A better understanding of the structure of a tornado system helps to determine what a hook echo represents on radar. The hook is located on the windward side of a steady-state thunderstorm echo. It forms in the convergence zone of this main echo. It is a small feature compared to the main storm and extends out to ten miles into the low-level flow. The hook appearance on radar normally precedes the formation of a tornado. The tops of hook echoes are usually near 20,000 feet. The hook develops in a short period and has a duration that is quite variable. The intensity of the tornado is dependent upon the sharpness of the hook echo.

A point that must be made quite clear is that no definite pattern can be stated for meteorological phenomena and this pattern is not necessarily followed by every occurrence of the hook-echo phenomenon. There must always be room left for consideration of large variations from this model and situations which do not comply in any manner. This brief paper is presented so the radar operators may have a better understanding of the phenomenon associated with the hook echo.

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Lt. John W. Stryker
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13. ABSTRACT

A great amount has been published on both tornado activity and hook echoes on radar. This paper discusses one popular tornado theory and explains the existence of the hook echo on radar. The tornado model used is that developed by the late Dr. Fred Bates.

On the basis of the tornado theory, a steady-state storm develops with a rotating updraft at the center of the storm. The potential for tornadic development is on the convergent or windward side of the cell.

The hook echo as viewed on radar, while not assumed to be the tornado itself, has an extremely high correlation with tornado occurrence or funnel cloud sightings. The question posed then is: What is this hook echo and how is it associated with the tornadic vortex? By using the model in the Bates Theory, a satisfactory conclusion can be derived

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